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# On Optimal Distributed Channel Allocation for Access Points in WLANs

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**Abstract.** We propose a new distributed algorithm for optimal channel assignment in WLANs with multiple access points, applying a novel formulation for wireless networks based on Distributed Constraint Optimization Problem (DCOP). The DCOP approach allows to model a wide variety of distributed reasoning tasks of multi-agent applications. The proposed strategy is derived from a polynomial-space algorithm for DCOP named ADOPT, which is guaranteed to find the global optimal solution while allowing agents to execute asynchronously and in parallel. Our proposed algorithm, denoted DCAA-O, allows a group of APs to coordinate themselves in order to find the optimal channel allocation solution which minimizes the network interference. The algorithm performance is evaluated in terms of the required number of transmitted control messages among APs. It is shown that DCAA-O outperforms a recently proposed channel assignment strategy for WLANs.

**Keywords:** Wireless Networks, Channel Assignment, Distributed Constraint Optimization Problem

## 1 Introduction

Typical deployments of Wireless Local Area Networks (WLANs) utilize multiple access points (APs) equipped with a single radio interface. Such networks can suffer from serious capacity degradation due to the half duplex nature of the wireless medium and also due to the interference between simultaneous neighboring transmissions. Fortunately the IEEE 802.11b/g and 802.11a standards [1], provide 3 and 12 non-overlapping channels, respectively, which could be used simultaneously within a neighborhood [2]. The ability to utilize multiple channels, benefiting from the whole available spectrum, substantially increases the capacity of wireless networks [3]. The implementation of a dynamic and distributed algorithm for channel allocation is fundamental to keep the network operating at its maximum capacity. Several methods have been proposed for dynamic spectrum access, including pricing and auction mechanisms and graph coloring. Some promising cooperative strategies for channel assignment have been recently proposed in the literature for application in WLANs [4] and mainly in wireless mesh networks (WMNs) [5, 6]. Specifically, our study about channel assignment focus on

WLAN scenarios. The existing distributed algorithms do not guarantee optimal solution and may present convergence instability. As many WLAN scenarios are typically not large enough to make an optimization approach unfeasible, we identify the lack of an optimal distributed strategy for channel allocation in order to reduce interference between APs in the same physical neighborhood. Additionally, we consider that APs in the same transmission range can opportunistically communicate among themselves over wireless channel to coordinate a distributed optimization process that guarantee the best solution for the experienced interference scenario. Such coordination approach over wireless channel allows the proposed algorithm to be applied to a wireless network formed by APs belonging to different WLANs.

The paper presents two main contributions. The first one is the novel formulation for the channel assignment problem as a DCOP and the second one is the proposal of a new distributed and synchronous algorithm called DCAA-O (Distributed Channel Assignment Algorithm - Optimal), which is able to reach the optimal frequency assignment, irrespective of the network topology, number of APs, network density and available channels. We compare DCAA-O with a recently proposed measurement-based algorithm, *Local-Coord* (LO-A), presented by Chen et al. in [4]. It was shown in [4] that LO-A performs better than algorithms proposed in [7–10]. The remainder of this paper is organized as follows. Section 2 describes DCOP and ADOPT algorithm [11]. In Section 3 we present the novel formulation for channel assignment in WLANs via DCOP. The proposed algorithm is described in Section 4. The evaluation scenario and results are presented in Sections 5 and 6. Section 7 concludes the paper.

## 2 Background

In artificial intelligence research area, a *distributed constraint optimization problem* (DCOP), consists of a set of variables that are distributed to a group of collaborative agents as *valued* constraints, that is, constraints that are described as valuable functions that return values in a specific range. The goal is to optimize a global objective function, maximizing the weight of satisfied constraints [11].

Consider a set of  $N$  agents,  $A = \{a_1, a_2, \dots, a_N\}$ , and a set of  $N$  values,  $D = \{d_1, d_2, \dots, d_N\}$ , where each value  $d_j$  is assigned to an agent  $a_j$  and belongs to a finite discrete domain  $\mathbb{D}_j$ . For each pair of agents  $(a_i, a_j)$  a cost function  $f_{ij}(x, y) : \mathbb{D}_i \times \mathbb{D}_j \rightarrow \mathbb{R}$  is defined. Agents have to coordinate themselves in order to find a set of values that optimize a global function establishing the costs for constraints. Therefore, the goal of a DCOP algorithm is to find the optimal set, denoted  $D^*$ , whose values minimize a global cost function  $g^* = g(D^*)$ .

Modi et al. [11] proposed Simple-ADOPT, the first algorithm for DCOP that can find the *optimal* solution, using only localized asynchronous communication and polynomial space at each agent. Simple-ADOPT is a backtracking search algorithm that is executed asynchronously and in parallel on every agent, updating lower bounds on global solution quality. The Simple-ADOPT algorithm requires agents to be prioritized in a total order, making use of a *spanning tree* (ST), obtained through Depth-First Search (DFS) [12]. The authors use the term *parent* to refer to an agent's immediate higher priority agent in the ordering and *child* to refer to an agent's immediate lower

priority agent in the ordering. Figure 1b shows the total order on agents for constraint graph of Figure 1a, represented by the ST generated by the DFS algorithm. Giving this ordering, an agent communicates its value  $d_j$  to all linked lower priority agents, as indicated in Figure 1c, and communicates a lower bound cost to a unique higher priority agent as indicated in Figure 1d.

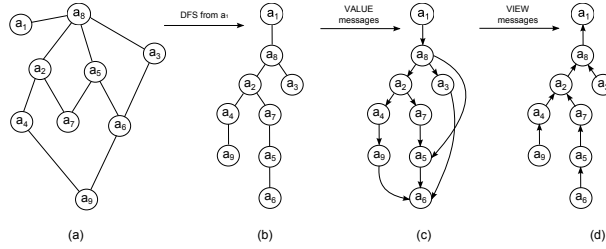
In order to change its value and lower bound cost information between agents, the Simple-ADOPT algorithm employs two types of control messages, denoted VALUE and VIEW messages respectively. The flow direction of VALUE and VIEW messages are also indicated in Figures 1c and 1d, respectively. These graphs are required input parameters for the Simple-ADOPT algorithm and they will be denoted as *VALUE graph* and *VIEW graph*, for short. Let  $P_j^{value}$  and  $C_j^{value}$  be the set of parents and children of an agent  $a_j$  in the *VALUE graph*, respectively. Likewise, let  $P_j^{view}$  and  $C_j^{view}$  be the set of parents and children of an agent  $a_j$  in the *VIEW graph*. A pair agent/value of the form  $(a_j, d_j)$  is called a *view*. The variable  $Currentvw_j$  of an agent  $a_j$  is the current set of *views*  $\{(a_{i1}, d_{i1}), (a_{i2}, d_{i2}), \dots, (a_{il}, d_{il})\}$ , composed by the all linked ancestor's agent/value pairs, which means that  $\{a_{i1}, a_{i2}, \dots, a_{il}\} \in P_j^{value}$ . The variable  $vw_j$  of an agent  $a_j$  stores the current view of agent  $a_j$  regarding his parent agent  $a_i \in P_j^{view}$  in the *VIEW graph*, denoted  $(a_i, d_i)_j$ . Therefore  $vw_j = (a_i, d_i)_j \in Currentvw_j$  of agent  $a_j$ . The variable  $Currentvw_j$  is sent to his parent agent  $a_i \in P_j^{view}$  using a VIEW message. When a parent agent  $a_i$  receives the VIEW message containing  $Currentvw_j$  from child agent  $a_j$ , it must perform a view compatibility test. We say that two views  $(Currentvw_j$  and  $Currentvw_i)$  are compatible if the views  $vw$  associated to the same parent nodes in the *VALUE graph* have the same value  $d$ , which means that  $\forall vw = (a, d) \in Currentvw_j$  we also have  $vw \in Currentvw_i$ .

Simple-ADOPT begins by each agent  $a_j$  choosing locally and concurrently a value  $d_j \in \mathbb{D}_j$ . This value is sent to all its linked descendent agents  $\{a_{k1}, a_{k2}, \dots, a_{kn}\} \in C_j^{value}$ , using VALUE messages. Then agents asynchronously wait for and respond to incoming messages. Given the received VALUE messages from parents agents, agent  $a_j$  chooses his local value  $d_j$  according to (1).

$$d_j = x \mid \min_{x \in \mathbb{D}_j} \sum_{a_i \in P_j^{value}} f_{ij}(d_i, x). \quad (1)$$

During the Simple-ADOPT algorithm execution, each agent  $a_j$  must deal with three distinct cost values, the *local cost*, the *current lower bound cost* and the *estimated lower bound cost*. The *local cost* is defined by  $lc_j = \sum_{a_i \in P_j^{value}} f_{ij}(d_i, d_j)$ . It is computed as sum of cost functions for all VALUE messages received from ancestors, using the chosen value  $d_j$  obtained from (1). The *current lower bound cost* for subtree is computed according to  $sc_j = \sum_{a_k \in C_j^{view}} z_k^*$ . It is the sum of all *estimated lower bound costs* received from children agents in the *VIEW graph*,  $\{a_{k1}, a_{k2}, \dots, a_{kn}\} \in C_j^{view}$ . The last one is the *estimated lower bound cost* defined by  $z_j^* = lc_j + sc_j$ , which is the sum of local cost  $lc_j$  with the cost  $sc_j$ . If an agent  $a_j$  does not have any descendent, his *estimated lower bound cost*,  $z_j^*$ , is just its local cost  $lc_j$ . Whenever an agent  $a_j$  receives a VALUE message from a *linked ancestor*  $a_i \in P_j^{value}$ , it stores the current received value  $(a_i, d_i)$  into his  $Currentvw_j$  variable, which represents  $a_j$ 's current context. For

its current context, the agent  $a_j$  then reports the estimated lower bound cost  $z_j^*$  to his parent agent  $a_i \in P_j^{view}$ , by a VIEW message. In its turn, his parent agent  $a_i$ , will use the received *estimated lower bound cost*  $z_j^*$  in order to compute its *current lower bound cost for subtree*,  $sc_i$ . The flow of VIEW messages is different from the flow of VALUE messages. The VALUE graph has its origin on the DFS tree plus all conflict edges existing between vertices in the undirected constraint graph  $G = (V, E)$  that is not represented in the DFS tree. Meanwhile the VIEW graph is exactly the DFS tree. The parent agent receives a VIEW message but throw away this message when  $vw_j \notin Currentvw_i$ . This situation can happen in two cases: either the parent agent  $a_i$  has a more up-to-date current view than its child  $a_j$  or  $a_j$  has a more current up-to-date view than its parent  $a_i$ . When an agent  $a_j$  reports to its parent  $P_j^{view}$ , its estimated lower



**Fig. 1.** DCOP Example: (a) Constraint graph; (b) Constraint graph of totally ordered agents; (c) Graph of VALUE messages; (d) Graph of VIEW messages

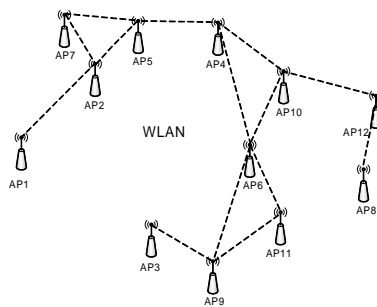
bound cost  $z_j^*$ , locally the agent assumes the value  $d_j$  that has minimized  $z_j^*$ . Finally, when an agent  $a_j$  receives a VALUE message, it updates its current context by updating the current values  $d_i$  of its parents. The agent then deletes its stored cost  $z_j^*$ , since it may now be invalid. Simple-ADOPT by storing only one current view, has linear space requirements at each agent, considering the number of variables that an agent can assume, represented by the finite discrete domain  $\mathbb{D}_j$ . The algorithm reaches a stable state when all agents are waiting for incoming messages. Then the complete assignment chosen by the agents is equal to the optimal assignment set, denoted  $D^*$ , whose values minimize a global cost function,  $g^* = g(D^*)$ .

### 3 Modeling Channel Assignment via DCOP

In WLANs a large number of access points may be operating in the same region, leading to a scenario where the *management* of wireless channels is extremely important because *co-channel* and *adjacent-channel* interference can significantly reduce the network performance. Consider the problem of optimizing the throughput of a WLAN with multiple APs. This requires that channels of all APs have to be set to maximize the signal-to-interference ratio. As the number of possible channels grows exponentially with the number of APs, we have a NP complex combinatorial optimization problem [13].

The approach of this work is to propose a distributed synchronous parallel method based on multi-agents concept [15], allowing any set of APs coordinate for searching the optimal solution for the channel allocation problem. Since the domains are inherently distributed, we require a method where agents can optimize a global function in a distributed way, using only local coordination (communication with neighboring agents). As our challenge is not only to ensure computational time but also to ensure an acceptable amount of exchanged messages between agents, we adopted a distributed synchronous and parallel solution, that unlike some conventional distributed approaches as Asynchronous Backtracking (ABT) [14] and the Synchronous Branch and Bound (SynchBB) algorithm in [16], ensures the optimal solution. The considered environment refers to one or more stationary wireless networks, composed by APs arbitrarily distributed over an area, where each AP is equipped with a single IEEE802.11b radio interface [1]. We consider the reduced problem where all radio interfaces across the network use omnidirectional antennas and have identical transmission powers. The goal is find the best channel allocation solution for each AP in order to improve the overall network performance.

In order to apply DCOP an undirected *constraint graph*  $G = (V, E)$  should be obtained from the physical network topology. Consider as an example a WLAN scenario composed of 12 APs, whose physical layout is shown in Figure 2. The dotted lines in Figure 2 represent the connectivity between APs. This means that their respective channel allocations will affect the performance of both due to the multiple access contention and interference. Therefore, the graph represented by the connections between APs in Figure 2 constitutes the *constraint graph* for the channel allocation problem. In such case, the set of vertices  $V$  of the constraint graph  $G$  represents the APs, and the set of conflict edges  $E \subseteq V^2$  is represented by connectivity links between APs. As described in Section 2 agents must be prioritized in a total order, making use of a *spanning tree*. An initialization procedure using a predefined common control channel is required allowing each AP to identify the APs in the neighborhood (constraint graph) and also to configure his logical ordering in the VALUE and VIEW graphs. This can be accomplished by means of a distributed spanning tree algorithm. After the logical graph construction each AP knows its parent, child, and linked descendants. Following



**Fig. 2.** Example of a physical WLAN deployment.

the approach used in [13] we consider a cost function metric based on channel spectrum overlapping. Specifically in North America and Europe, there are 11 different channels that an AP may select in IEEE802.11b/g 2.4GHz ISM band. This ISM band is allocated between 2400 and 2483MHz, with channel central frequencies starting at 2412MHz and spaced at 5MHz intervals to 2462MHz. As the channel bandwidth is about 22MHz, there is a substantial spectrum overlap between adjacent channels. If adjacent APs select overlapping channels, it will be induced a spectral interference between concurrent transmissions or multiple access contention. An accurate interference model is necessary taking into account the level of spectrum overlap. For instance, a 5.5 or 11Mbps DSSS (Direct Sequence Spread Spectrum) unfiltered modulated signal has a power spectrum behavior described by:

$$\mathcal{S}(n, f) = \begin{cases} \left| \frac{\sin[2\pi\mathcal{X}(n, f)]}{2\pi\mathcal{X}(n, f)} \right|^2, & \text{for } \mathcal{X}(n, f) \neq 0 \\ 1, & \text{for } \mathcal{X}(n, f) = 0 . \end{cases} \quad (2)$$

where  $\mathcal{X}(n, f) = \frac{f-2412-5(n-1)}{BW}$ ,  $BW$  is the null-to-null channel bandwidth and  $n$  is the channel number ( $n = 1, 2, \dots, 11$ ). The WLAN cards employ an IF filtering on both transmit and receive paths in order to reduce sidebands power. The approximated IF filter power spectrum response is defined by  $\mathcal{F}(n, f) = [1 + 2.6 \mathcal{X}(n, f)]^{-6}$  [13]. It has 3dB bandwidth of 17MHz and stopband 50dB down at  $\pm 22$ MHz. From (2) we can now determine the channel overlap factor, which determines the co-channel interference level between two APs. The spectrum overlap factor  $\mathcal{SO}(n, m)$  between the channel number  $n$  and the channel number  $m$  is given by (3). The overlap factor can be normalized by the maximum overlap factor which occurs when both channels are the same. The normalized factor is defined by (4) as a function of the channel spacing,  $c_{spc} = n - m$ , where  $n \geq m$  and  $c_{spc} \in \{0, 1, 2, \dots, 10\}$ . Table 1 presents the normalized overlap factor  $\mathcal{SO}_{norm}$  as a function of channel spacing  $c_{spc}$ , obtained using (4). Its is important to point out that the numerical results shown in Table 1 may vary for different chipset and filter configurations of the WLAN card.

$$\mathcal{SO}(n, m) = \int_{2200}^{2700} \mathcal{S}(n, f) \mathcal{F}(n, f) \mathcal{S}(m, f) \mathcal{F}(m, f) df . \quad (3)$$

$$\mathcal{SO}_{norm}(c_{spc}) = \frac{1}{\mathcal{SO}(1, 1)} \int_{2200}^{2700} \mathcal{S}(1, f) \mathcal{F}(1, f) \mathcal{S}(c_{spc} + 1, f) \mathcal{F}(c_{spc} + 1, f) df . \quad (4)$$

In our DCOP formulation, the selected value  $d_j$  of an agent  $a_j$  represents the channel selection number of the AP <sub>$j$</sub> , therefore the domain of  $d_j$  is defined as  $\mathbb{D}_j = \{1, 2, \dots, 11\}$ . For a pair of connected agents (pair of interfering APs) in the constraint graph, the cost function for a pair of values  $(d_i, d_j)$  is defined as  $f_{ij}(x, y) : \mathbb{D}_i \times \mathbb{D}_j \rightarrow \mathbb{R}$  where the values in  $\mathbb{R}$  represent the interference overlap factors of Table 1. The APs by coordinating themselves have to find a set of channel allocation values,  $D^*$ , that optimizes a global function establishing the costs for constraints that minimize the total amount of interference. In practice, the channel overlap factor can be weighted by a normalized path loss weighting factor denoted by  $\alpha_{ij}$  where  $0 \leq \alpha_{ij} \leq 1$ , resulting in a

**Table 1.** Adjacent Channel Interference Factor

| Channel Spacing | Overlap Factor |
|-----------------|----------------|
| 0               | 1              |
| 1               | 0.7272         |
| 2               | 0.2714         |
| 3               | 0.0375         |
| 4               | 0.0054         |
| 5               | 0.0008         |
| 6               | 0.0002         |
| 7 - 10          | 0              |

local cost,  $\alpha_{ij} f_{ij}(x, y)$ , between the APs. The parameter  $\alpha_{ij}$  can be computed by agent  $a_i$  based on the received signal strength intensity (RSSI) of the received message from agent  $a_j$ . In this study we consider the worst case interference scenario where  $\alpha_{ij} = 1$ .

#### 4 Proposed Algorithm

The Simple-ADOPT algorithm operates asynchronously and in parallel on every agent. In many multi-agent applications this is not a restriction but, in our case, this is an undesirable characteristic because we want to minimize the number of overhead messages among APs. Therefore, we derived DCAA-O from Simple-ADOPT keeping the optimality conditions and imposing synchronous message control at agents. Our algorithm employs the same basic notation for parents and children nodes, as well as the definition of VALUE and VIEW graph. The pseudocode of the proposed DCAA-O method is shown in Algorithm 1. The parameters listed below are also based on the description of ADOPT, however some changes were necessary for the development of our algorithm.

- $a_j$ : Current Access Point;
- $a_1$ : Root Access Point;
- $A'_i$ : Set of APs descendent of an ancestor  $a_i \in P_j^{value}$ ;
- $P_j^{value'} = P_j^{value} \cap A'_i$ : Subset of  $P_j^{value}$  whose nodes are descendent of an ancestor  $a_i \in P_j^{value}$ ;
- Currentvw** $_j = \{(a_i, d_i^t)\}, \forall a_i \in P_j^{value}$  : Current view of AP  $a_j$ ;
- LocalCosts** $_j = \{[d_j^t, lc_j(d_j^t), sc_j(d_j^t)]\}, \forall d_j^t \in \mathbb{D}_j$  : Temporary Local Costs of AP  $a_j$  for each choice  $d_j^t$ ;
- SubTreeValues** $_j(d_j^t) = \{(a_j, d_j^t), (a_k, d_k), \dots\}, \forall a_k \in \text{subtree of } a_j$  : Temporary subtree costs;
- $lc_j(d_j^t)$  : Local cost of AP  $a_j$  given  $d_j^t$  and **Currentvw** $_j$ ;
- $sc_j(d_j^t) = \sum_{a_k \in C_j^{view}} z_k(d_j^t)$ : Subtree cost of  $a_j$ ;
- $z_j(d_j) = lc_j(d_j) + sc_j(d_j)$  where  $d_j = x \mid \min_{x \in \mathbb{D}_j} lc_j(x) + sc_j(x)$ ;

The choice of the value  $d_j$  is an important point of the distributed algorithm execution. A given node  $a_j$  will iterate with its subtree, through its VALUE and VIEW children, for different temporary  $d_j^t \in \mathbb{D}_j$  choices. During the iteration, the node  $a_j$  builds its variables, **LocalCosts** $_j$  and **SubTreeValues** $_j$ . After testing all  $d_j^t$ , the node



is able to identify the value  $d_j$  that minimizes the cost of the subtree in the context represented by  $z_j(d_j)$ . From this time the node  $a_j$  sends a VIEW message to its parent  $a_i \in P_j^{view}$ , that can continue with its procedure for choosing its local channel  $d_i$ . The DCAA-O algorithm can initiate the channel reallocation in a network composed of multiple APs, when an AP identifies co-channel or adjacent channel interference. In a preliminary step the AP  $a_j$  initiates a distributed algorithm for calculating the spanning tree [17, 18] that allows the definition of VALUE and VIEW graphs on all nodes. After the execution of the algorithm, as presented in Algorithm 1, the root node sends a message identified as *TERMINATE*, containing optimal allocation solution for all other APs through the graph VALUE.

The algorithm DCAA-O was implemented and simulated in a distributed way, using a library of discrete event simulation denoted *SIMPATICA* [19], based on the actors/messages paradigm. According to this paradigm, a simulation model is composed by a set of actors (or tasks) that communicate among them using messages. This library allowed us to simulate a distributed synchronous environment through three kinds of entities: task, queue and message. Each AP is implemented as a task and has three queues for receiving messages, VIEW\_QUEUE, VALUE\_QUEUE, and TERMINATE\_QUEUE, respectively.

## 5 Evaluation Scenario

The performance of DCAA-O was evaluated on random generated network topologies. We considered topologies of 4, 9 and 16 nodes, with graph densities of 1, 2, 3, 4 and 5, when applicable. A graph with *link density*  $d$  has  $d \cdot n$  links, where  $n$  is the number of nodes in the graph [11]. For a given number of nodes, a total of 30 random topologies was generated for each density. As a first study scenario, we allowed the APs to select the corresponding channel from an available set with only three channels, composed of the tree *non-overlapping* channels  $\{1, 6, 11\}$ . In the second scenario APs can select one among 11 available channels. We compared the proposed algorithm to the scalable distributed algorithm, denoted *Local-Coord* (LO-A), recently proposed by Chen et al. [4]. LO-A is a simple distributed algorithm, featuring a good balance between solution quality and number of messages exchanged between the APs. However to their considered environment, an AP needs to locally coordinate with others APs via a wired backbone network for channel switching. For comparison purposes, LO-A messages are exchanged among APs via a pre-defined wireless control channel as for DCAA-O.

## 6 Simulation Results

The performance of DCAA-O was evaluated in terms of the average number of exchanged messages between APs for convergence to optimal solution. The LO-A algorithm was used as a benchmark algorithm. The stopping criterion for LO-A algorithm concerns to a minimum number of iterations without any improvement or new channel allocation among the APs. We considered a lower bound of 50 iterations for LO-A. This value was determined by simulation as an appropriate criterion to stop the execution of the LO-A algorithm. Table 2 presents the comparison results for topology scenarios

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**Algorithm 1: DCAA-O**

---

```
1 Procedure Initialization
2   Currentvwj = ∅;
3   LocalCostsj = ∅;
4   SubTreeValuesj(dj) = ∅ ∀dj ∈  $\mathbb{D}_j$ ;
5 end

6 Procedure RootNode
7   forall the (d1t ∈  $\mathbb{D}_1$ ) do
8     Send_VALUE_Message(a1, d1t) ∀ak ∈ C1value;
9     forall the (ak ∈ C1view) do
10      Receive_VIEW_Message(ak, zk(dk), SubTreeValuesk(dk);
11      SubTreeValues1(d1t) =
12      SubTreeValues1(d1t) ∪ SubTreeValuesk(dk);
13      sc1(d1t) = sc1(d1t) + zk(dk);
14    end
15    Add [d1t, 0, sc1(d1t)] to LocalCosts1;
16  end
17  d1 = x | minx ∈  $\mathbb{D}_1$  sc1(x), where sc1(x) ∈ LocalCosts1;
18  Send_TERMINATE(SubTreeValues1(d1)) ∀ak ∈ C1view;
19 end

19 Procedure OtherNodes
20 while TERMINATE_QUEUE = ∅ do
21   Receive_VALUE_Message(ai, dit);
22   Add (ai, dit) to Currentvwj;
23   forall the (ai ∈ Pjvalue') do
24     Receive_VALUE_Message(ai, dit);
25     Add (ai, dit) to Currentvwj;
26   end
27   forall the (djt ∈  $\mathbb{D}_j$ ) do
28     lcj(djt) = ∑ai ∈ Currentvwj fij(dit, djt);
29     scj(djt) = 0;
30     Add [djt, lcj(djt), scj(djt)] to LocalCostsj;
31   end
32   if (Cjvalue ≠ ∅) then
33     forall the (djt ∈  $\mathbb{D}_j$ ) do
34       Send_VALUE_Message(aj, djt) ∀ ak ∈ Cjvalue;
35       forall the (ak ∈ Cjview) do
36         Receive_VIEW_Message
37         (ak, zk(dk), SubTreeValuesk(dk));
38         SubTreeValuesj(djt) =
39         SubTreeValuesj(djt) ∪ SubTreeValuesk(dk);
40         Add zk(dk) to scj(djt) in LocalCostsj;
41       end
42     end
43   end
44   dj = x | minx ∈  $\mathbb{D}_j$  lcj(x) + scj(x), where lcj, scj ∈ LocalCostsj;
45   zj(dj) = lcj(dj) + scj(dj);
46   SubTreeValuesj(dj) = SubTreeValuesj(dj) ∪ {(aj, dj)};
47   Send_VIEW_Message(aj, zj(dj), SubTreeValuesj(dj)) to
48   ai ∈ Pjview;
49 end
50 Receive_TERMINATE(SubTreeValues1(d1));
51 Set channel dj = dm | aj = am, (am, dm) ∈ SubTreeValues1(d1);
52 Send_TERMINATE(SubTreeValues1(d1)) ∀ak ∈ Cjview;
53 end
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with 4 APs. In this case the random generated network topologies may only have graph density one. The DCAA-O algorithm presented a number of exchanged messages at least 90% smaller than LO-A. The final global cost value obtained by both algorithms was the same and is omitted here for brevity. The performance evaluation of DCAA-O and LO-A for random topologies formed by 9 APs is shown in Figure 3. For the case of 3 available channels, DCAA-O presented lower values for the average number of exchanged messages compared to LO-A (around 50% less). However for the case of 11 channels, although reaching the optimal solution to the cost function, DCAA-O requires a larger number of exchanged messages for convergence than LO-A. As shown in Figure 4, it is important to note that DCAA-O always finds the optimal solution for every scenario, whereas LO-A algorithm achieves suboptimal values for graph densities 1, 2 and 3. For the case of 9 APs with density 4, the suboptimal values obtained by LO-A are close to optimal solution found by DCAA-O. The same conclusions also apply for scenarios with greater densities or with a larger number of nodes, as we observed in topologies with 16 APs. The results for 16 APs were omitted for brevity. It is important to point out that we also validated the DCAA-O solution optimality in each scenario by means of exhaustive search in the solution space. It is important to point out that the final global cost is directly related to the throughput performance metric because it measures the overall network interference. Therefore, by using the analytical cost model we do not need to run extensive throughput simulations.

**Table 2.** Average Number of Messages - Topologies with 4 APs

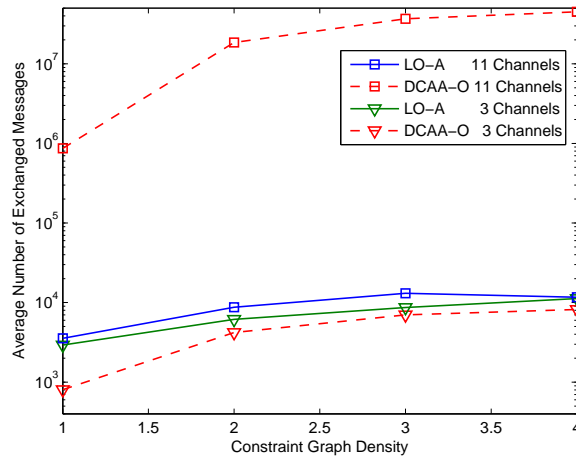
| Available Number of Channels | DCAA-O | LO-A |
|------------------------------|--------|------|
| 3 Channels                   | 29     | 1324 |
| 11 Channels                  | 277    | 2140 |

## 7 Conclusions

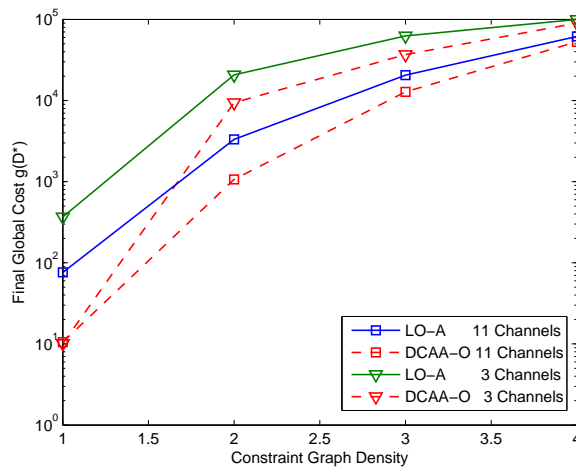
The work reported in this paper combines artificial intelligence (AI) research methods with wireless network optimization problems, addressing the channel assignment in WLANs as a *distributed constraint optimization problem*. The proposed algorithm (DCAA-O) achieves the optimal solution for the channel assignment problem, therefore reducing the adjacent channel interference and maximizing the network performance. The required average number of exchanged messages among APs to reach optimal solution demonstrated to be inferior to LO-A for some specific scenarios. Scenarios with a larger number of APs and higher densities must be investigated in order to reduce the number of exchanged messages in DCAA-O.

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**Fig. 3.** Performance of DCAA-O and LO-A (9 APs)



**Fig. 4.** Final global cost value for DCAA-O and LO-A (9 APs)

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